Electron earthward transport in the Earth magnetotail: adiabatic convection heating and scattering-induced losses

Pavel Shustov[1], Anton Artemyev[1,2], Anatoliy Petrukovich[1]

[1]Space Research Institute, RAS, Moscow, Russia

[2]University of California Los Angeles, Los Angeles, USA

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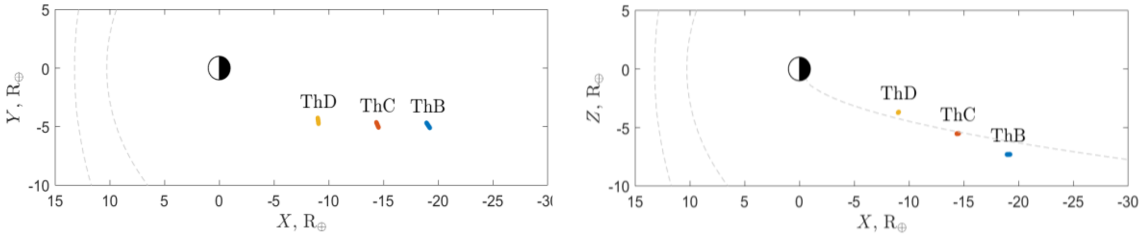
Outline

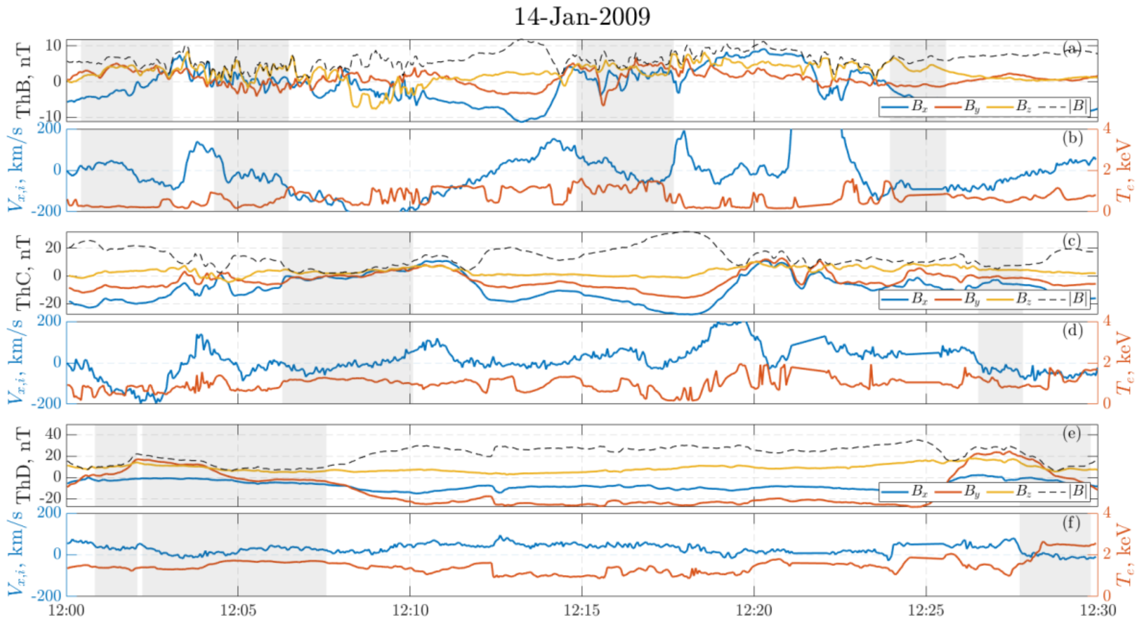
1. Data
   - Themis Events overview
   - Is adiabatic heating sufficient?
2. Model
   - Distribution function evolution
3. Data/model comparison
   - Electron spectra with electron losses
   - Loss cone angle estimation
4. Conclusions and discussions

Data: Events

We use statistics of events when three THEMIS spacecraft ThB, ThC, ThD observe the magnetotail current sheet within one hour. We select 6 events when reliable measurements of electron velocity distributions are available for all three spacecraft.



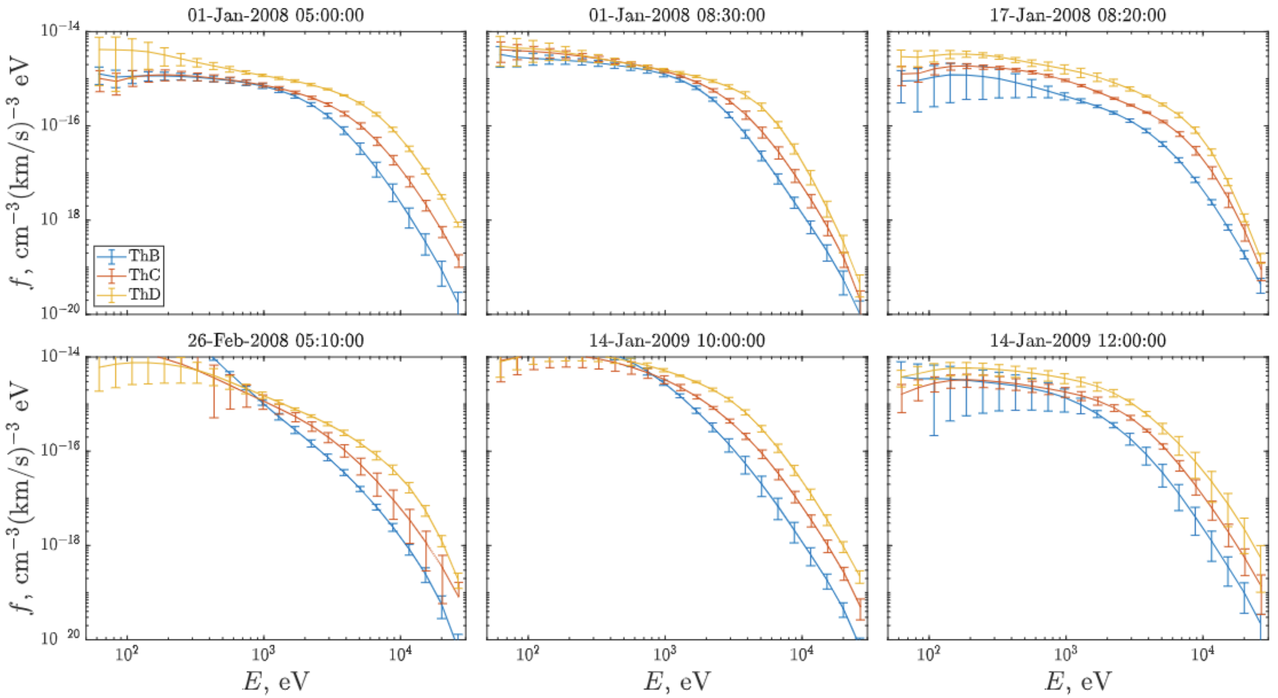
#	Date	Time	Duration (min)
1.	01-Jan-2008	05:00	30
2.	01-Jan-2008	08:30	60
3.	17-Jan-2008	08:20	30
4.	26-Feb-2008	05:10	20
5.	14-Jan-2009	10:00	30
6.	14-Jan-2009	12:00	30



The example of one of selected events for three satelites (ThB, ThC, ThD): magnetic field components (three top panels), ion bulk flow, and electron temperature. Grey color shows sub-intervals with small Bx (equatorial plane) and small Vx (unperturbed magnetotail). We analyze plasma and field measurements from such sub-intervals for each events (from table).

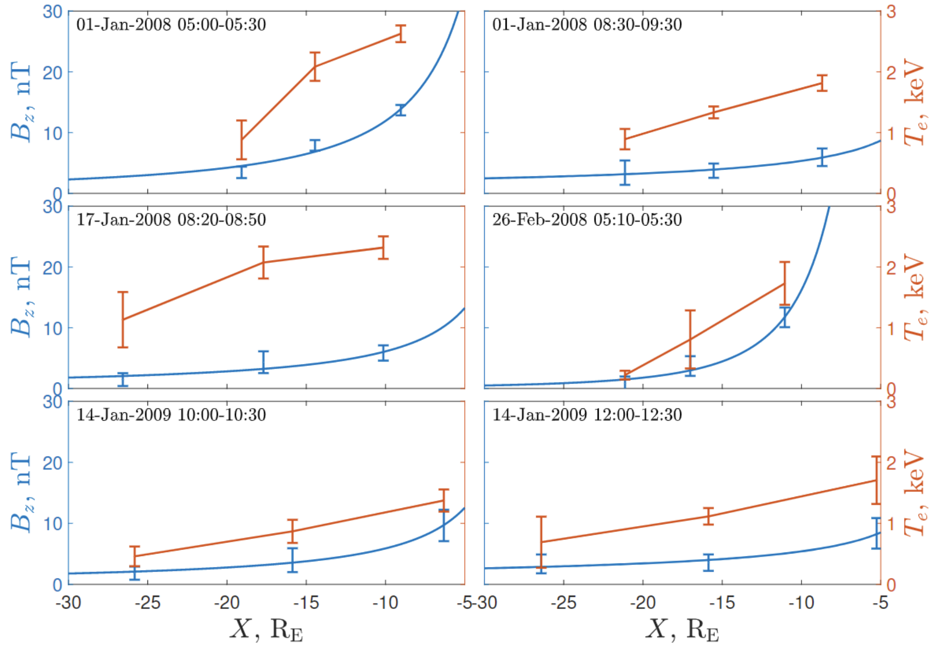
We obtain data – electron distribution function – in the equatorial plane of the unapertured magnetotail at three different distances from the Earth ($\sim 10R_E$, $\sim 15R_E$, $\sim 20R_E$) in the same time interval.

Data: Events overview



Electron distribution functions from the three THEMIS spacecraft during the six events. For $E > 1\ keV$ the phase space density drops exponentially, and we see strong hierarchy with the distance here.

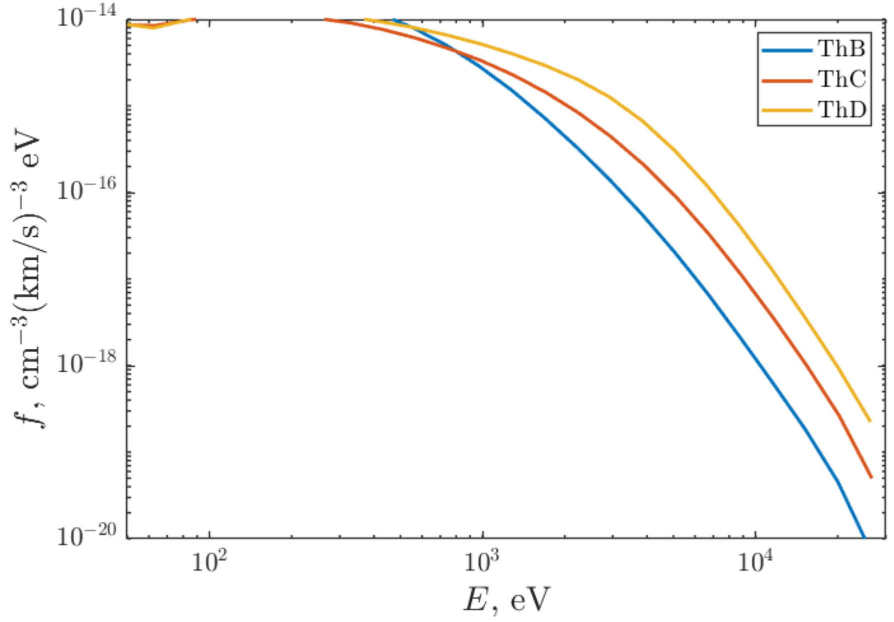
We also examine the electron flux anisotropy for all events – it is larger than one only for E < 1 keV.



Electron temperature $T_e(x)$ and magnetic field $B_z(x)$ during the six events from Table at ThB, ThC and ThD possitions with time averaging over near-current-sheet subintervals for each event. Blue curve corresponds to power-law fit obtained by least squares method.

Data: Is adiabatic heating sufficient?

An example of simultaneous Themis observations of the near neutral plane average spectra.

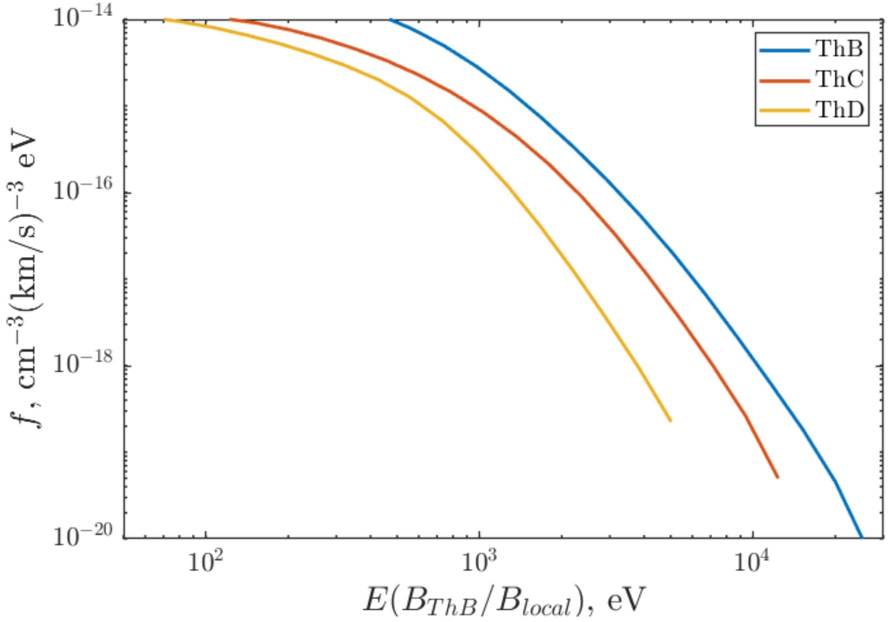


Adiabatic energy change:

$E/B_z = const$

ThB – the farthest
ThD – the closest
to Earth

The spectra adiabatically shifted to the same magnetic field.



All three spectra should coincide when energy normalized to the magnetic field (right figure).
But we always see that normalized furthest to the Earth specter (ThB, blue) shows much higher phase space density than near-earth spectra (ThC and ThD).

Consequently, it is necessary to consider the losses of electrons.

Model: Distribution function evolution

Distribution function evolution with losses:

$$\frac{\partial f}{\partial t} = \frac{\partial f}{\partial \varepsilon}\dot{\varepsilon} - \frac{1}{\tau_{loss}} f$$

Adiabatic energy change with power fit:

$$\varepsilon = \varepsilon_0 \left(\frac{B_z}{B_{z0}}\right)^q$$

Loss function:

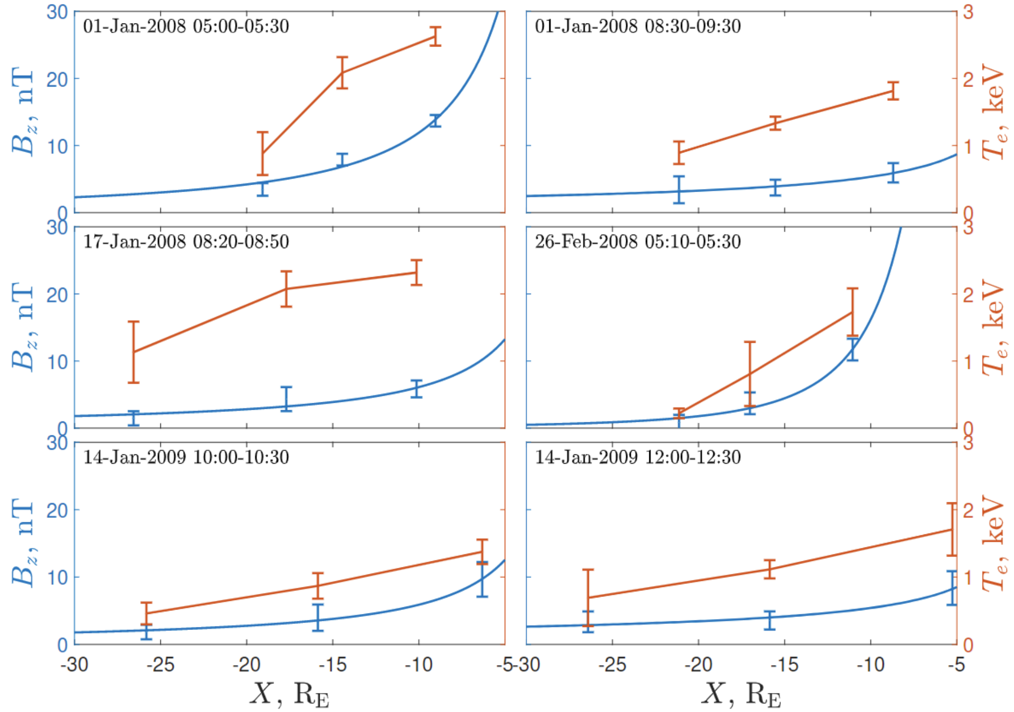
$$\frac{1}{\tau_{loss}} = \begin{cases} 0, & \varepsilon < \varepsilon_1 \\ \frac{1}{\tau_0}\left(\frac{\varepsilon}{\varepsilon_1} - 1\right)^{\beta}, & \varepsilon \geq \varepsilon_1 \end{cases}$$

Using electron drift velocity, we substitute the time derivatives with the x derivatives, and then rewrite the drift equation

$$\frac{\partial f}{\partial t} = \frac{\partial f}{\partial \varepsilon}\dot{\varepsilon} - \frac{1}{\tau_{loss}} f \quad \rightarrow \quad \frac{\partial f}{\partial x} = \frac{\partial f}{\partial \varepsilon}\frac{\varepsilon}{l(x)} - \frac{1}{V(x)}\frac{f}{\tau_{loss}(\varepsilon)}$$

where $V(x) = cE_y/B_z(x)$, $l(x) = q^{-1}\,\partial \ln B_z(x)/\partial x$

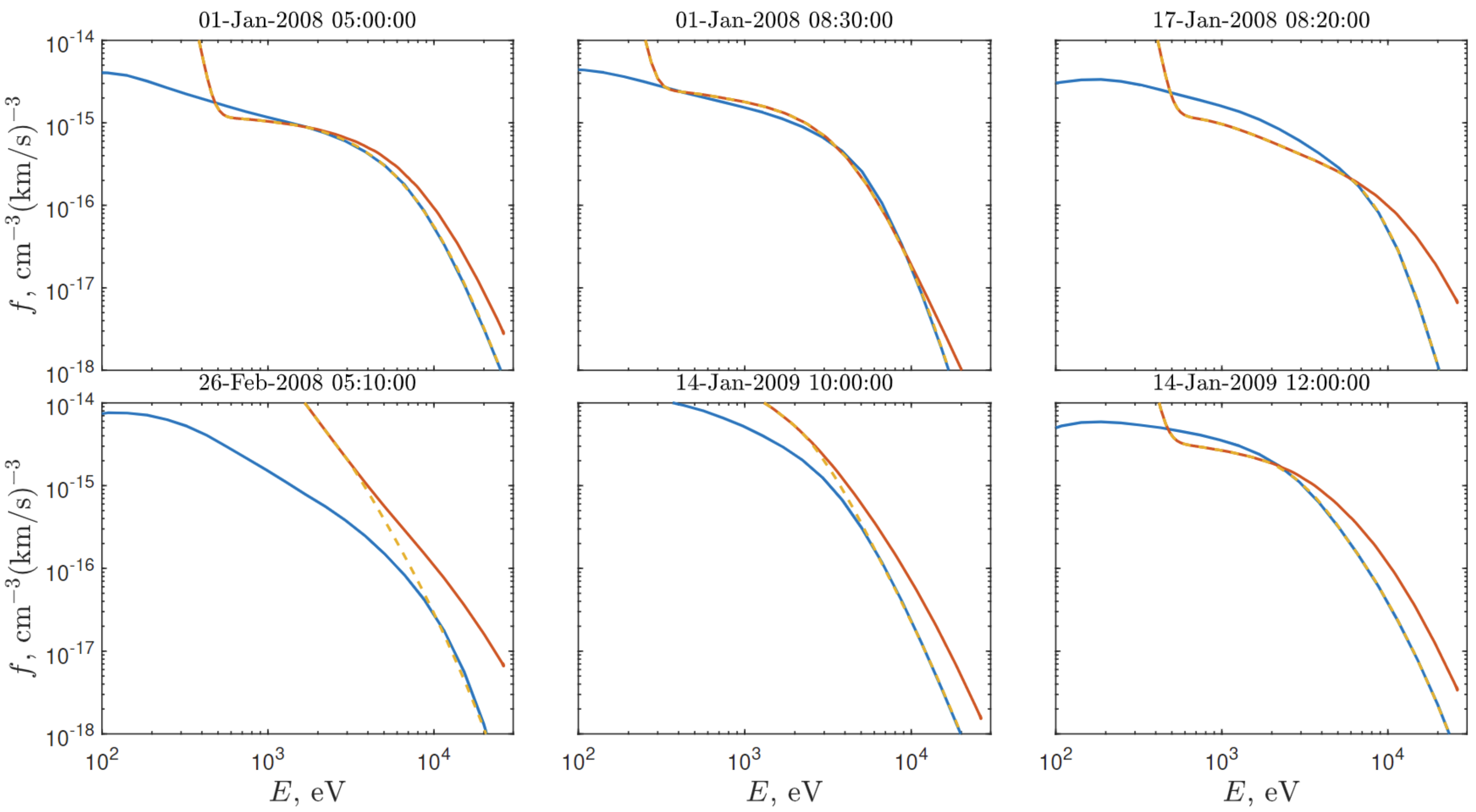
Now distribution function depends only on function $B_z(x)$, and parameters $E_y = 0.05 - 0.2$ mV/m, $q = 0.8$.



Magnetic field function $B_z(x)$ is polynomial fit $B_z(x) = b_0 x^{-p}$ of observed averaged B_z value.

Data/model comparison: Electron spectra with losses

We assume that the drift equation should describe the observed electron spectra, and then compare data and model to estimate loss time



By variating τ_{loss} function parameters β, τ_0 and ε_1, it is possible to achieve coincidence of distribution functions at high energies.

$$\frac{1}{\tau_{loss}} = \begin{cases} 0, & \varepsilon < \varepsilon_1 \\ \frac{1}{\tau_0}\left(\frac{\varepsilon}{\varepsilon_1} - 1\right)^{\beta}, & \varepsilon \geq \varepsilon_1 \end{cases}$$

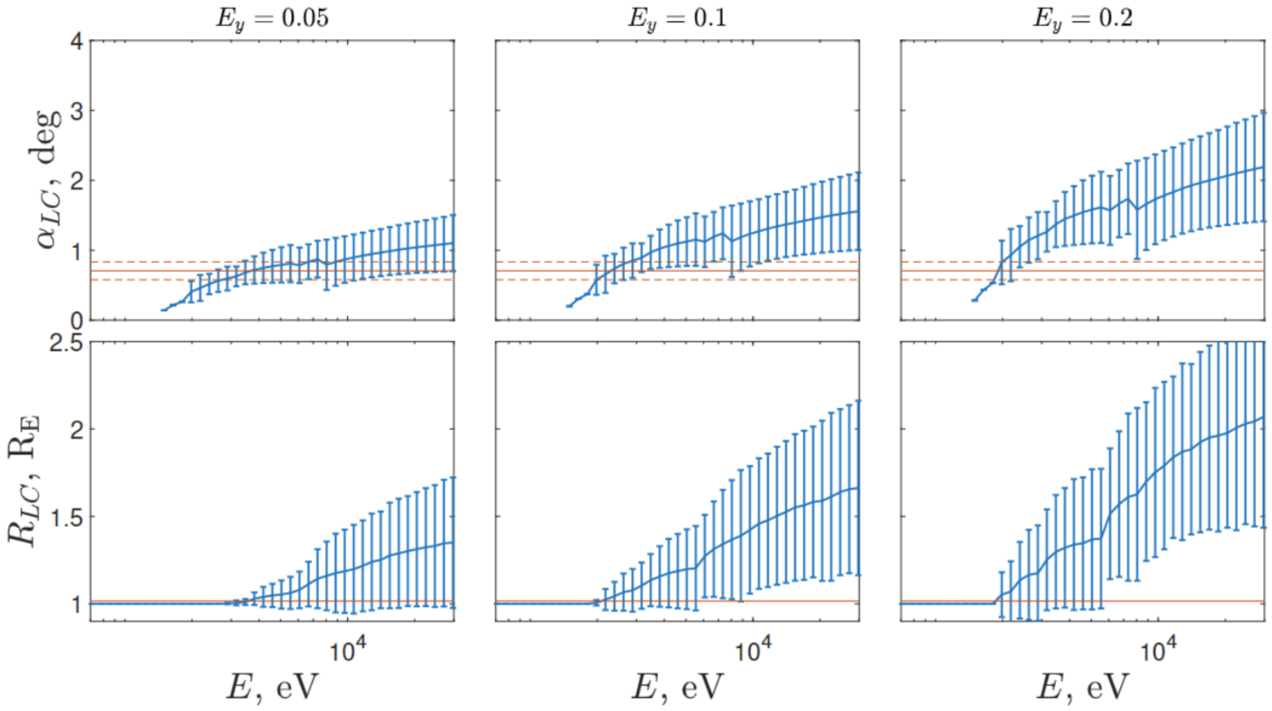
#	β	τ_0	ε_1
1.	0.6	10440	700
2.	0.9	6480	1000
3.	0.75	792	4000
4.	0.9	1152	8000
5.	0.58	3060	1000
6.	0.38	1674	1600

Data-model comparison: Loss cone angle estimation

Loss cone estimation: the reason of the electron loss it the pitch angle diffusion and precipitation.
Strong diffusion limit: $\tau_{loss} \lesssim \tau_{LC} = \tau_b / 4\alpha_{LC}^2$, τ_{loss} – determinate by electrons spectra comparison, bounce period is a function $\tau_b = \sqrt{m_e/2\varepsilon}\, g(B(s); \alpha_{LC})$.
Thus, we can estimate the loss cone angle α_{LC}, which corresponds to the strong diffusion limit

Loss-cone size needed to describe observed electron losses.
Red horizontal line shows the loss-cone angle corresponding to the ~100km altitude

The radial distance R_{LC} of electron losses corresponding to estimated α_{LC}
Red line shows ionosphere altitude.



The reflection point of the lost particles could not be significantly above the surface of the Earth. However, one can see that electrons precipitate much higher than the ionosphere (R_{LC}>0). This indicates that:

- *The filling of the loss cone occurs in the limit of strong diffusion*
- *Particles are lost significantly higher than the ionosphere, e.g., in the area of auroral acceleration*

Results

1. We have shown that electron loss has a significant effect on the electron spectrum formation and significantly limits the population of hot electrons in the near-Earth magnetotail.

2. The losses of electrons is about the limit of strong diffusion — observations in the magnetotail indicate that the loss cone should be filled.

3. Losses exceeding the strong diffusion limit may be explained by the loss of electrons in the auroral acceleration region ($\sim 0.5 - 1$ R_E) above the ionosphere)

The results of this work is published in JGR:
Shustov, P. I., et al, (2021). Evolution of thermal electron distributions in the magnetotail: Convective heating and scattering-induced losses. Journal of Geophysical Research: Space Physics, 126, e2021JA029952. https://doi.org/10.1029/2021JA029952